AFRL-SR-AR-TR-04-

0416

## REPORT DOCUMENTATION PAGE



| 1. REPORT DATE *(DD-MM-YYYY)* | 2. REPORT TYPE | 3. DATES COVERED *(From - To)* |
|---|---|---|
| | Final | 1 December 2000 - 31 March 2003 |

**4. TITLE AND SUBTITLE**
Neural Network Based Adaptive Control of Uncertain and Unknown Nonlinear Systems

**5a. CONTRACT NUMBER**

**5b. GRANT NUMBER**
F49620-01-1-0024

**5c. PROGRAM ELEMENT NUMBER**

**6. AUTHOR(S)**
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**5d. PROJECT NUMBER**

**5e. TASK NUMBER**

**5f. WORK UNIT NUMBER**

**7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)**
Gerogia Institute of Technology
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20040810 028

**9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)**
Air Force Office of Scientific Research
4015 Wilson Blvd
Mail Room 713
Arlington, VA 22203

AFOSR

**11. SPONSOR/MONITOR'S REPORT NUMBER(S)**

**12. DISTRIBUTION/AVAILABILITY STATEMENT**
Distribution Statement A. Approved for public release; distribution is unlimited.

**13. SUPPLEMENTARY NOTES**

**14. ABSTRACT**
The objectives of this research effort were to exploit recent advances in neural network (NN) based adaptive control, with the goal of being able to treat a very general class of nonlinear system, for which the dynamics are not only uncertain, but may in fact be unknown except for minimal structural information, such as the relative degree of the regulated output variables. We were particularly interested in designing adaptive control systems that are robust with respect to both parametric uncertainty and unmodeled dynamics. Extensions to decentralized control were also of interest. In addition, we placed a high priority on transition opportunities in aircraft flight control, control of flows, control of flexible space structures, and control of aeroelastic wings.

**15. SUBJECT TERMS**

| 16. SECURITY CLASSIFICATION OF: | | | 17. LIMITATION OF ABSTRACT | 18. NUMBER OF PAGES | 19a. NAME OF RESPONSIBLE PERSON |
|---|---|---|---|---|---|
| a. REPORT | b. ABSTRACT | c. THIS PAGE | | | Anthony J. Calise |
| | | | | | 19b. TELEPHONE NUMBER *(Include area code)* 404-894-7145 |

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

8-5-04

# Research in Neural Network Based Adaptive Control

**Final Report**

1 December 2000 to 31 March 2004

Research Supported by:
Air Force Office of Scientific Research
4015 Wilson Blvd, Room 713
Arlington, VA 22203-1954

**Award No:** F49620-01-1-0024

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# Contents

# 1. Objectives

The objectives of this research effort were to exploit recent advances in neural network (NN) based adaptive control, with the goal of being able to treat a very general class of nonlinear system, for which the dynamics are not only uncertain, but may in fact be unknown except for minimal structural information, such as the relative degree of the regulated output variables. We were particularly interested in designing adaptive control systems that are robust with respect to both parametric uncertainty and unmodeled dynamics. Extensions to decentralized control were also of interest. In addition, we placed a high priority on transition opportunities in aircraft flight control, control of flows, control of flexible space structures, and control of aeroelastic wings.

# 2. Accomplishments

## 2.1 Accomplishments in Year-1

*Adaptive Output Feedback Control,[J2,J3,J2&J3-Year2,C6,C10]:* Output feedback control architectures typically make use of state estimation, and therefore require that the dimension of the plant be known. Existing approaches either restrict the output to have full relative degree, or restrict the uncertainties in the plant to be dependent only on the output variables. Development of an adaptive output feedback approach for highly uncertain systems that overcomes these restrictions has been the main thrust of our research during the past several years. Our efforts this year have resulted in two promising approaches [J3]. The first is a *direct* adaptive control. The second uses a novel, non-adaptive error state observer. The controller architectures have proven not only to be robust to unmodeled dynamics, but also have the capability to interact with and control these dynamics. The control architecture for the first approach is shown in Figure 1. The main features of this architecture include the dynamic compensator, with an additional output $(\tilde{y}_{ad})$ used in the NN training algorithm, and a delayed signal generation block, the outputs of which are used as inputs to the NN and are utilized to estimate the model inversion error from past measurements.

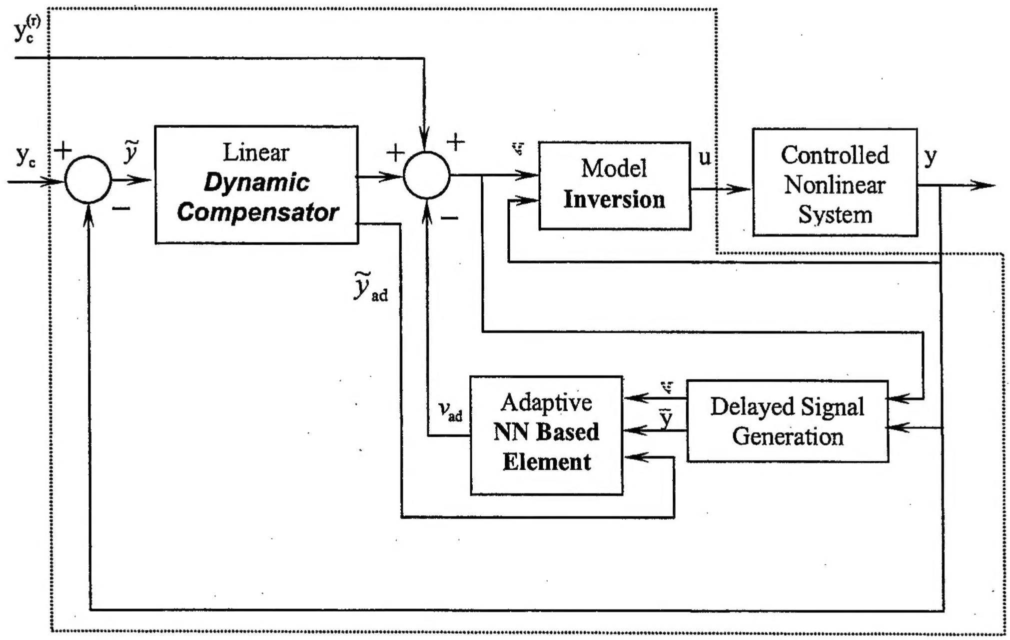



Fig. 1 The adaptive output feedback control architecture.

The delayed signal generation block is common to both approaches. We have considered general SISO systems represented by the system equations

$$\dot{x} = f(x,u)$$
$$y = h(x)$$

where $x \in R^n$ is the system state vector, $u$ is the scalar control input, $y$ is the scalar measurement and regulated output, and $f(\cdot,\cdot)$ and $h(\cdot)$ are partially known, or unknown sufficiently smooth functions. Additional outputs, which are not regulated, may be incorporated into the design approach. The only modeling assumption is that the relative degree $(r \le n)$ of the output is known. Thus, the $r^{\text{th}}$ derivative of the output is the first derivative of the output that is "strongly" affected by the control, i.e.

$$y^{(r)} = h_r(x,u)$$

where $h_r(x,u)$ is also a partially known, or unknown function. Feedback linearization is performed by introducing the transformation

$$v = \hat{h}_r(y,u)$$

where $\hat{h}_r(y,u)$ is the best available *invertible* approximation of $h_r(x,u)$, and $\nu$ is commonly referred to as pseudo-control. Since only the measured signal can be used for control, a dynamic compensator is introduced to stabilize the linear portion of the tracking error dynamics, and the NN operates only on the available input/output data. Under the assumption that the plant is observable, we have shown that the unknown model inversion error can be mapped from present and past input/output data [J2-Year2]. The delayed signal generation block of Fig.1 provides the inputs required for this function.

One of the immediate advantages of our result is that the dimension of the plant (dimension of the state vector $x$) is not needed in the design, and the only information required is the relative degree of the measured signal. Thus, the result is applicable to plants having both unstructured parametric uncertainty and unstructured unmodeled dynamics.

<u>*Example:*</u> Consider a two-degree of freedom system

$$\dot{x}_1 = x_2$$
$$\dot{x}_2 = -2(x_1^2 - 1)x_2 - x_1 + u$$
$$\dot{x}_3 = x_4$$
$$\dot{x}_4 = -x_3 - 0.2x_4 + x_1$$

with regulated output given by

$$y = x_1 + x_2$$

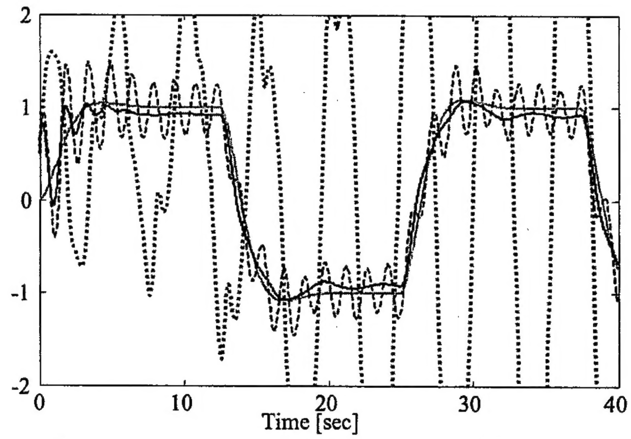


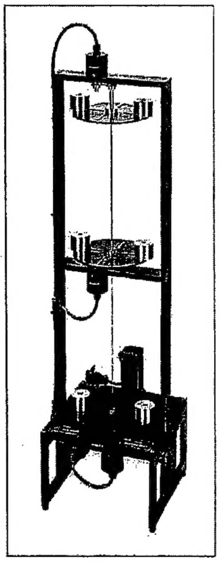
Figure 2. Responses With Unmodeled Dynamics

The output $y$ has a relative degree of two. The system can be though of a nonlinear single degree of freedom rigid body ($x_1$ and $x_2$ states) coupled to a lightly damped unmodeled mode. The unmodeled mode is excited by the rigid body dynamics and is coupled to the output. Ideally we wish to regulate only $x_1$, and not the measurement $y$. The low natural frequency of the unmodeled mode is encompassed by the bandwidth of the control design. Moreover, the inverting design is performed without knowledge of the nonlinearities in the rigid body mode. This presents a very difficult control design challenge. Figure 2 shows the $x_1$ state responses with neural network adaptation gains of 0, 10 and 50, and compares these responses with the command filter output (smooth line). The response without adaptation (dotted line, adaptation gain = 0) is unstable, due to the unmodeled mode. The response progressivly improves and approaches the command as the adaptation gain is increased. This demonstrates the ability of the output feedback approach to accommodate both parametric uncertainty (in the rigid body dynamics) and unmodeled dynamics (the added mode). An illustration is given in [C3] that addresses nonlinear modeling of the actuation process and the use of 'hedging' in the adaptive process, but for the case of state feedback. An application to flight control currently undergoing flight testing is described in [C10].

*Decentralized Adaptive Control, [J2-Year2]:* We have developed an adaptive decentralized state feedback control architecture for large-scale systems with interconnections being bounded linearly by their tracking error norms. The local subsystems are assumed to be feedback linearizable. Future research will investigate removing this last assumption, and possible extensions to the output feedback case.

## 2.2 Accomplishments in Year-2

*Augmenting Linear Controllers,[C7, C14]:* Most work in adaptive control for nonlinear systems assumes that an inverting type of control is used for the non-adaptive portion of the control system design. Considering that the vast majority of existing controllers are not based on inversion, it would be highly desirable to retrofit such systems with an adaptive element. Moreover, there are many applications in which inverting design is not an option, such as control of large flexible systems. Existing methods of augmenting linear controllers are restricted to state feedback, and impose restrictive conditions. For example they might require that the regulated variable have full relative degree, or that the plant uncertainty is matched. Also, since these methods are based on comparing the state response of an idealized model with the true plant, they cannot be applied to situations in which the true plant dynamics, including the disturbance process dynamics, are higher order that the model used to design the linear controller. Therefore they are not robust with respect to unmodeled dynamics. Flexible systems provide a good example in which state feedback based approaches are not useful. The controller architecture we have developed can be applied without any of the restrictions mentioned above[A1,A2,C1,C11]. The only restriction is that the relative degree of the regulated output is known. The approach has been applied to a 3-disk pendulum laboratory model. An example experimental result is depicted in Fig. 3. In this result, the disturbance process is applied to the upper disk, and the response of the lower disk is controlled. The disturbance consists of a combination of sinusoids. The response with NN on shows a significant improvement over the response for a linear controller designed using a rigid body model. This dramatically demonstrates that our design is not only robust to unmodeled dynamics, but is also adaptive to these dynamics, including the dynamics of the disturbance process as well. We are currently developing an extension of this research that can be applied to non-minimum phase systems[C14].



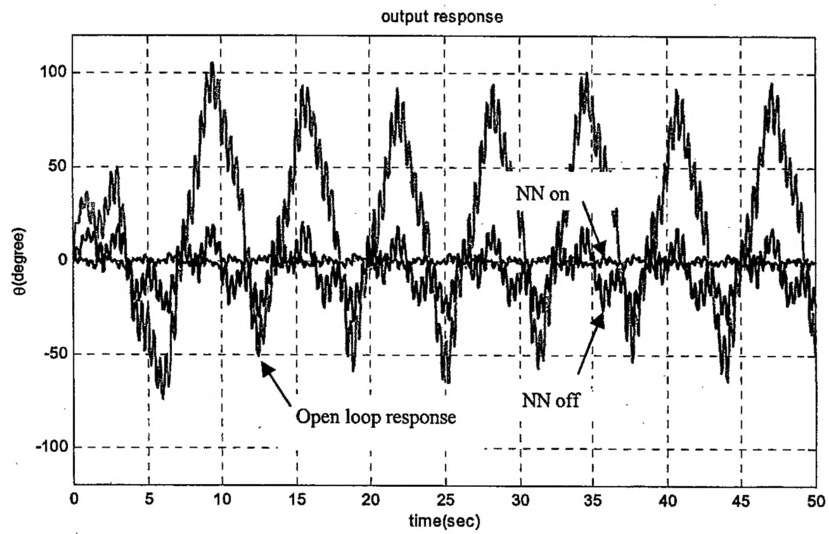



Fig. 3. Experimental result depicting adaptive control of a flexible system.

Decentralized Adaptive Control: Decentralization and cooperation are diametrically opposed objectives. That is, the need to cooperate gives rise to a greater need for communication. The problem of bringing multiple vehicles into close formation is a prime example. To achieve both decentralized and cooperative control, we need to demonstrate that it is possible for a member of a group of vehicles to 'learn' the behavior of at least its neighboring vehicles by observing their relative motions. This should be possible since swarms in nature achieve this using vision as their primary sensing modality. The objective during this period has been to mathematically formulate a problem that would form the basis for such a demonstration, and to test this formulation in simulation. Consider a group of N vehicles whose individual dynamics are defined by

$$\begin{aligned} \dot{x}_i &= f_i(x_i, d_i, u_i)\ ,\ i = 1,2,\ldots,N \\ y_i &= h_i(x_i) \end{aligned} \tag{1}$$

In (1) $d_i$ is a vector of disturbance processes acting on the $i^{th}$ vehicle, $u_i$ is the vehicle's control vector, and $y_i$ denotes a set of local variables to be controlled. Assume that the vehicles cooperate by controlling a joint variable

$$z = g(\overline{x}) \tag{2}$$

where $\overline{x}$ is the union of the state vectors of all the vehicles within the group. Let the relative degree of $z$ be $r$, so that

$$\begin{aligned} z^{(i)} &\equiv \frac{d^i z}{dt^i} = g_i(\overline{x}, \overline{d}), \qquad i = 1 \ldots r-1 \\ z^{(r)} &= g_r(\overline{x}, \overline{d}, \overline{u}) \end{aligned} \tag{3}$$

To arrive at a decentralized control solution, the following approximation is employed by the $i^{th}$ vehicle

$$\hat{z}_i^{(r)} = \hat{g}_{ri}(x_i, z, u_i) \tag{4}$$

Eq. (4) forms the basis for an inverting control design in which the modeling error is

$$\Delta_i = g_r(\bar{x}, \bar{d}, \bar{u}) - \hat{g}_{ri}(x_i, y, u_i) \tag{5}$$

Each vehicle's inverting solution is augmented with an adaptive element that estimates and approximately cancels $\Delta_i$. The degree to which this can be accomplished is a measure of the degree to which it is possible for one vehicle to 'learn' the behavior of the other vehicle by observing its relative motions. Fig. 4 compares the resulting trajectories obtained for a 2-D engagement model in whichAircraft 1 regulates heading as its local variable, and both aircraft cooperate in regulating range. The center portion of this figure shows what happens using the NN adaptive control approach of Ref. A1. The right portion of this figure compares the NN output with the modeling error (6) for Aircraft 2.

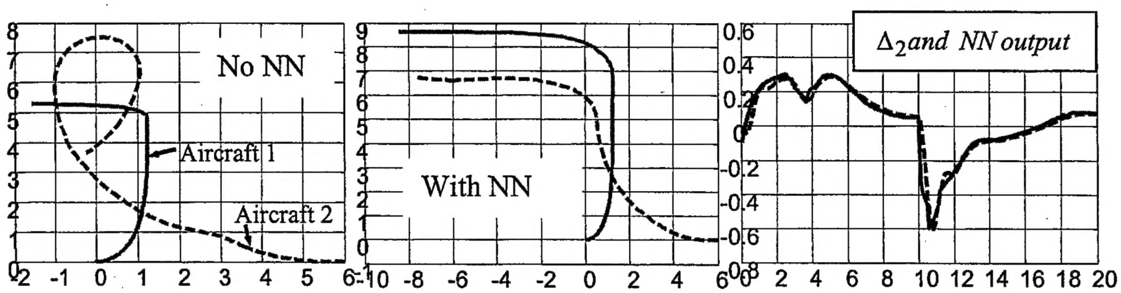



Fig. 4. The role of adaptation in decentralized adaptive flight control.

<u>Adaptive State Estimation [C13]</u>: Existing methods for nonlinear state estimation impose assumptions that severely limit their domain of applicability, such as to systems that are linear with respect to unknown parameters, or systems that can be transformed to output feedback form. NN based adaptive observers have relaxed some of these assumptions; however robustness to unmodeled dynamics and disturbances was not shown in the most general case. We have developed a methodology for adaptive state estimation of bounded nonlinear processes by augmenting an existing linear observer with two neural networks that model the uncertainties from a finite history of available measurements[J4-Year3]. Fig.3 illustrates the performance of our adaptive observer for a nonlinear process[C13] and compares it to the performance of the linear observer. The simulated dynamics have a combination of unmodeled sinusoidal and step disturbances.

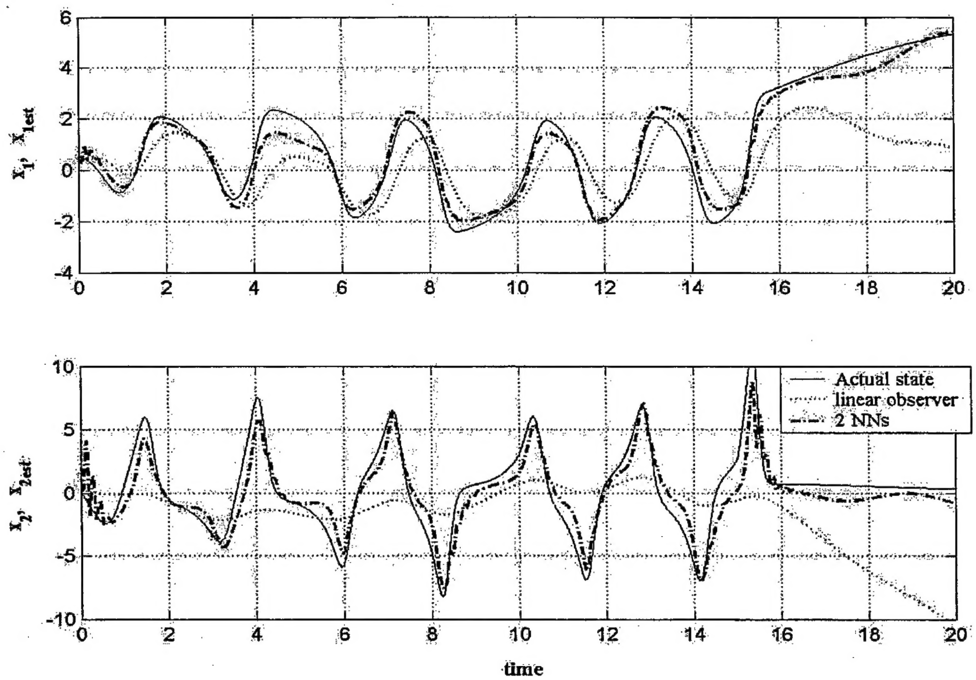



Fig.5 Performance of a two NN augmented adaptive observer.

### 2.3 Accomplishments in Year-3

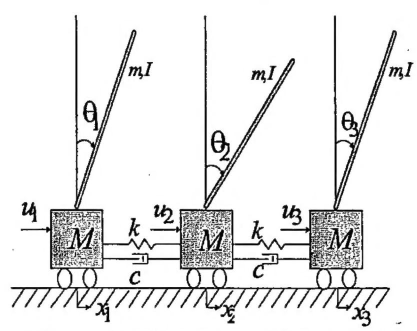


Fig. 6. Configuration of 3 Inverted

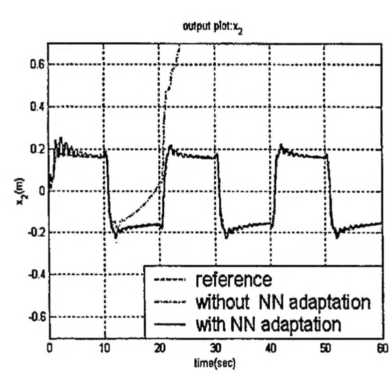



Fig. 7. Output Responses.

*Decentralized adaptive output feedback[C1, C2, S5]:* This is formulated as a control design problem for a system composed of dynamically interconnected subsystems, with the requirement that the controller for each subsystem utilize only locally sensed outputs to cause a subset of these outputs to track a reference command. Distributed systems, or systems with an array of sensors and actuators, are one technology area motivating the design of decentralized controllers, as are large space structures and large flexible wings. The main problem in this area concerns the manner in which the dynamic interconnections are treated in the design process. In general, the interconnections may depend upon the entire state and control of the large-scale system. The status of our current effort in this direction[C1, C2] demonstrates how one can achieve decentralized adaptive output feedback tracking with bounded errors, if the reference model states of each subsystem are known to all the controllers. Our results are valid for output feedback for a general class of nonlinear systems, without a restriction on relative

degree. However, we show only local ultimate boundedness of error signals. The assumption that the states of all the subsystem references models are known to each controller may be justified when considering coordinated control of large-scale systems, where a higher level centralized controller exists that broadcasts all the subsystem commands to every controller. However, there exist many situations where this assumption does not apply, or is not desirable. In particular, many large-scale systems in nature, commonly referred to as swarms, exhibit highly coordinated motions, without the use of a higher level authority. This is particularly important when operating in an uncertain environment. This research effort will be directed at achieving this behavior in an engineered system. If this theoretical breakthrough is achieved, it suggests that one can, for example, control a large complex structure by installing sensor/actuator packages over the structure, and have each adapt to control the local behavior. Figure 6 illustrates three masses, each supporting an inverted pendulum[C2]. The dynamics are nonlinear, non-minimum phase, and the equilibrium condition with $\theta_i = 0$ is unstable. Each nominal controller (without NN augmentation) is designed to track a position command while maintaining $\theta_i = 0$ . The coupling between the masses is ignored, and the designs are decentralized. None of the states of the decoupled systems are communicated to the adaptive element. Figure 7 illustrates the response of the center with and without NN augmentation.

*Formation Flight Control [C9, C12, C19]*: In a collaborative effort with Boeing[C9, C12] we have recently been looking at adaptive control of two aircraft in a closed-couple formation. The control problem is associated with control design for the *trailing* aircraft. Flying in formation, the trailing aircraft must constantly seek an optimal relative position that minimizes the aerodynamic drag force induced by the wing tip vortices of the lead aircraft. At the heart of this approach is the fact that it relies on utilizing a NN to compute an approximation of the local extremum of an unknown function to be minimized. The point is that adaptive extremum seeking control relies on the NN to not simply reduce a tracking erring signal, but instead to create an internal model of the function being minimized. Therefore, the ultimate success of this approach to optimization will rely heavily on the development of adaptive laws that are focused on internally modeling the uncertainty in the system. Future research will be focused on this direction.

A second area in which we have made considerable progress is that of controlling a swarm of vehicles attempting to fly a formation within a field of obstacles[C19]. In considering the problem of formation control in the deployment of intelligent munitions, it would be highly desirable, both from a mission and a cost perspective, to limit the information that is transmitted between vehicles in formation. However, the lack of information regarding the state of motion of neighboring vehicles can lead to degraded performance and even instability. We have developed an adaptive output feedback approach for addressing this problem. We design adaptive formation controllers that allow each vehicle in formation to maintain separation and relative orientation with respect to neighboring vehicles, while avoiding obstacles. The method works by enabling each vehicle in the formation to adaptively correct for the effect that the motions of neighboring vehicles have when regulating relative variables like range and line of sight. It is assumed that estimates of these variables can be derived using passive, vision-based sensors. The need for explicit communication to maintain formation is minimized and the resulting controller solution is

decentralized. We implement a reactive obstacle avoidance controller to navigate in an environment with obstacles. The formation controller and obstacle avoidance controller are outer-loop controllers whose outputs are speed and heading commands. These commands are blended together to generate composite speed and heading commands that are inputs to the inner-loop controller. The weights used for blending the commands depend upon the priority of the task at hand. Figures 8 and 9 illustrate the method with an example involving a team of three aircraft keeping formation in the presence of obstacles.

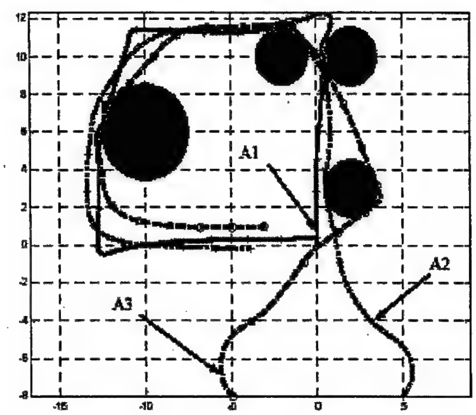



Fig. 8. Trajectory without NN Adaptation.

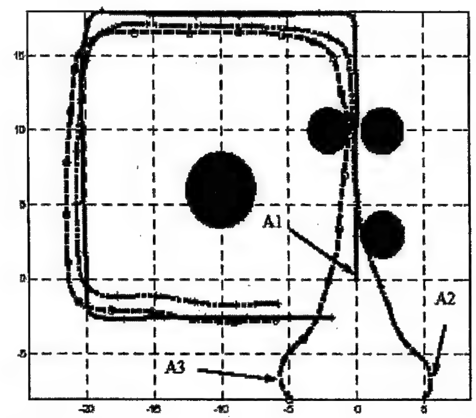



Fig. 9. Trajectory with NN Adaptation.

*Other Accomplishments:* Several of our previous publications in the area of adaptive output feedback control have appeared in journal versions[J1-J3]. An extension to MIMO systems appears in [S2] and to non-minimum phase systems in [S4]. We also have a new result on asymptotic tracking using multiplayer NNs [S6]. In addition we have provided a rigorous proof on the reconstruction of continuous time dynamics using delayed outputs[J4].

# 3. Transitions

*Guided Munitions, [J1]:* Completed Phase-III SBIR effort with Guided Systems Technologies. This work is aimed at demonstrating that a single tail kit with a fixed autopilot design can be used to control a wide class of guided munitions. Also, the autopilot design must accommodate changes in mission profiles, and not require accurate aerodynamic data. Two highly successful flight tests were completed at Eglin AFB.

**Government Customer:** AFWL, Eglin AFB

POC: Johnny Evers, 850-882-2961 x3330, evers@eglin.af.mil

***Corporate Customer:*** *Boeing Phantom Works*

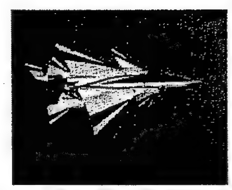
POC: Kevin Holt, 636-925-5114, kevin.d.holt@boeing.com

*Adaptive Control of Flexible Vehicles [C9]:* Two collaborative efforts funded by industry. Both utilize our adaptive output feedback approach to deal with flexible dynamics in flight control applications. The goal of this research is to overcome the problems encountered in designs that employ structural filters. We have shown that it may be possible to eliminate the use of structural filters all together.

**Corporate Customers: Raytheon and Lockheed**

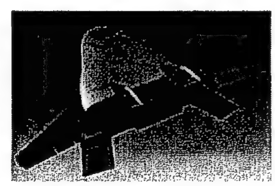
Technical POCs: Mike McFarland, 520-794-0592, mbmcfarland@west.raytheon.com
Jim Buffington, :817-935-1030, james.m.buffington@lmco.com

*Intelligent Flight Control System Design for the F15:* The goal of this effort is to design and evaluate a Neural Network (NN) based adaptive control algorithm for NASA's F-15 aircraft. Dr. Calise is developing the flight control software, and will provide on-site flight test support. Ultimately this research will be transitioned to a C-17 aircraft.



***Government Customers: NASA Ames/Dryden Flight Research Center***

Technical POC: Mr. John Burken, (661) 276-3726, john.burken@dfrc.nasa.gov



*Integrated Adaptive Guidance and Flight Control for Launch Vehicles, [C10]:* Our approach has completely eliminated the need for gain tables and makes no use of the aerodynamic data set. We have demonstrated adaptation to both force and moment perturbations due to failure. Current work also includes on on-line trajectory generation and adaptation for abort trajectories.

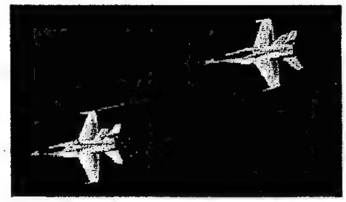
***Government Customers:*** *NASA Marshall and WPAFB*

Technical POCs: Dr. John Hanson, 256-544-2239, john.hanson@msfc.nasa.gov
Dr. Anhtuan D. Ngo, (937) 255-8494, anhtuan.ngo@va.afrl.af.mil

**Corporate Custormers:** Boeing

Technical POCs: Dr. Eugene Lavretsky, (562) 982-9269, eugene.lavretsky@boeing.com
Mr. Sunil Tandon, (714) 896-2680, sunil.tandon@boeing.com

*Formation Flight Control, [C9, C12]:* New flight control design approach was developed for multi UAV formations aimed at extending range and endurance. The solution relies on adaptive control and online extremum command generation. The developed methodology mimics piloting techniques during a closed coupled formation flight.



**Government Customer:** NASA Dryden Flight Research Center
Technical POC: John Burken, 661-276-3726, john.burken@dfrc.nasa.gov
**Corporate Custormer:** Boeing
Technical POCs: Dr. Eugene Lavretsky, (714) 235-7736, eugene.lavretsky@boeing.com

*Adaptive Control of Advanced Fighter Aircraft in High $\alpha$ Flight Regimes.: [C21]:* The goal of this effort is to demonstrate the use of dynamic inversion based adaptive output feedback control for high angle of attack flight control. The approach is being applied to an F-15 ACTIVE model with thrust-vectoring capability. The model is valid up to 60° angle-of-attack and includes Thrust Vector Control (TVC). The main objective of the control design is to demonstrate adaptation to aerodynamic uncertainty in the form of both unmodeled parameter variations and unmodeled dynamics not present in the nominal inversion design.

**Government Customer:** NASA Langley Research Center
Technical POC: Mark Motter, (757) 864-6978, m.a.motter@larc.nasa.gov

## 4. Consultations

Prof. Calise spent 4 months working with Johnny Evers (Eglin AFB), in the area of Adaptive Guidance and Flight Control, October 01 – April 02. Visiting position was arranged through the University of Florida GERC. Dr. Hovakimyan participated in an NSF "CAREER" proposals review panel in November 01.

*Prof. Calise* worked in collaboration with Dr. Eugene Lavretsky and Dr. Kevin Wise of the Boeing Phantom Works in applying neural network based adaptive control to Boeing's UCAV configuration. The approximate time period of this collaboration was from 12/02 to 4/03.

# 5. Publications

Year-1 Publications: {J-journal, C-conference}

J1. Calise, A.J., Sharma, M. and Corban, J.E. "Adaptive Autopilot Design for Guided Munitions," AIAA Journal of Guidance, Control, and Dynamics, Vol. 23, No. 5, 2000, pp 837-843.
J2. Hovakimyan, N., Rysdyk, R. and Calise, A.J., "Dynamic Neural Networks for Output Feedback Control," International Journal of Robust and Nonlinear Control, Vol.11, No.1, 2001, pp 23-39.
J3. Calise, A.J., Hovakimyan, N., and Idan, M., "Adaptive Output Feedback Control of Nonlinear Systems Using Neural Networks," Automatica, Vol.37, No.8, 2001.
C1. Nardi, F. Calise, A.J., "Robust Adaptive Nonlinear Control using Single Hidden Layer Neural Networks", Conference on Decision and Control, Sydney, Australia, December 2000.
C2. Johnson, E.N., Calise, A.J. and Corban, J.E., "Adaptive Guidance and Control for Autonomous Launch Vehicles, IEEE Aerospace Conference, Big Sky, MT, April 2001.
C3. Idan, M., Calise, A.J., Kutay, A.T., and Parekh, D.E., "Adaptive Neural Network Based Approach for Active Flow Control, ASME Fluids Engineering Division Summer Meeting, New Orleans, Louisiana, May 2001.
C4. Johnson, E.N., Calise, A.J., "Neural Network Adaptive Control of Systems with Input Saturation," American Control Conference, Arlington, Virginia, June 2001.C5.
C5. Idan, M., Johnson, M.D. and Calise, A.J., "Intelligent Aerodynamic/Propulsion Flight Control For Flight Safety: A Nonlinear Adaptive Approach," American Control Conference, Arlington, Virginia, June 2001.
C6. Hovakimyan, N., Nardi, N. and Calise, A.J., "A Novel Observer Based Adaptive Output Feedback Approach for Control of Uncertain Systems," American Control Conference, Arlington, Virginia, June 2001.
C7. Johnson, E.N., Calise, A.J., "Reusable Launch Vehicle Adaptive Guidance and Control Using Neural Networks, AIAA Guidance, Navigation, and Control Conference, Montreal, Canada, August, 2001.
C8. Idan, M., Johnson, M.D. and Calise, A.J., "A Hierarchical Approach to Adaptive Control fo Improved Flight Safety, AIAA Guidance, Navigation, and Control Conference, Montreal, Canada, August, 2001.
C9. Sharma, M., Calise, A.J., "Neural Network Augmentation of Existing Linear Controllers, AIAA Guidance, Navigation, and Control Conference, Montreal, Canada, August, 2001.
C10. Hovakimyan, N., Kim, N., Calise, A.J. and Prasad, J.V.R., "Adaptive Output Feedback for High Bandwidth Adaptive Control of an Unmanned Helicopter," AIAA Guidance, Navigation, and Control Conference, Montreal, Canada, August, 2001.

Year-2 Publications: {J-journal, C-conference}

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## 6. Patents and Invention Disclosures

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